

Evolution of Spin Direction of Accreting Magnetic Protostars and Spin-Orbit Misalignment in Exoplanetary Systems

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ABSTRACT

Recent observations have shown that in many exoplanetary systems the spin axis of the parent star is misaligned with the planet’s orbital axis. These have been used to argue against the scenario that short-period planets migrated to their present-day locations due to tidal interactions with their natal discs. However, this interpretation is based on the assumption that the spins of young stars are parallel to the rotation axes of protostellar discs around them. We show that the interaction between a magnetic star and its circumstellar disc can (although not always) have the effect of pushing the stellar spin axis away from the disc angular momentum axis toward the perpendicular state and even the retrograde state. Planets formed in the disc may therefore have their orbital axes misaligned with the stellar spin axis, even before any additional planet-planet scatterings or Kozai interactions take place. In general, magnetosphere–disc interactions lead to a broad distribution of the spin–orbit angles, with some systems aligned and other systems misaligned.

Key words: accretion, accretion discs – planetary systems: protoplanetary discs – stars: magnetic fields

1 INTRODUCTION

1.1 Background

Transiting planets are providing new ways to characterize exoplanetary systems. In particular, the Rossiter-McLaughlin (RM) effect, an apparent radial velocity anomaly caused by the partial eclipse of a rotating parent star by its transiting planet, can be used to measure the sky-projected stellar obliquity, the angle between the stellar spin axis and the planetary orbital axis. As of August 2010, sky-projected stellar obliquity has been measured in 28 systems¹ using the RM effect (see Triaud et al. 2010; Winn et al. 2010). Among these, about 60% have an orbital axis aligned (in sky projection) with the stellar spin, while the other systems show a significant spin-orbit misalignment, including 5 systems with retrograde orbits (e.g., Hébrard et al. 2008; Winn et al. 2009; Johnson et al. 2009; Narita

et al. 2009; Pont et al. 2010; Jenkins et al. 2010; Triaud et al. 2010). In addition, a recent analysis of the stellar rotation velocity shows that in 10 out of a sample of 75 exoplanetary systems there is likely a significant degree of misalignment along the line of sight between the planetary orbital axis and the stellar spin axis (Schlaufman 2010).

It is generally accepted that close-in exoplanets (“hot Jupiters”) are formed at a distance of order several AU’s or larger from their host stars before migrating inwards to their current locations. Gravitational tidal interaction between a gaseous disc and a young planet (Goldreich & Tremaine 1980) provides a natural mechanism for the inward planet migration (Lin et al. 1996; see Lubow & Ida 2010 for a recent review). Gas-driven migration alone, however, is unlikely to explain the observed eccentricity distribution for planets with periods longer than a few weeks. Two other processes have been suggested to play a role in shaping the architecture of exoplanetary systems: (i) Strong gravitational scatterings between planets in a multiplanet system undergoing dynamical instability (e.g., Rasio & Ford 1996; Weidenschilling & Marzari 1996; Zhou et al. 2007; Charterjee et al. 2008); (ii) Secular Kozai interactions between a

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¹ The number has increased to 48 in October 2010 (A. Triaud, private communication).

planet and a distant companion (a star or planet) in a highly inclined orbit (Wu & Murray 2003; Fabrycky & Tremaine 2007; Wu et al. 2007; see also Eggleton & Kiseleva-Eggleton 2001) or between planets in a multiple systems (Nagasawa et al. 2008). Both scatterings and Kozai interactions are expected to cause eccentricity in the final planetary orbits and misalignment between the stellar spin and the planetary orbit axis.

Newly formed planets are expected to lie in same plane as the gas disc. It is usually presumed that the planet-disc interaction preserves the alignment between the gaseous disc and the orbit of the planet. Under the assumption that the stellar spin is aligned with the disc angular momentum axis, planetary systems with zero or small stellar obliquity would be produced. The discovery of a significant fraction of misaligned systems (particularly the retrograde systems) has been suggested as a blow against the theory of disc-driven migration, and to favor the Kozai cycles plus tidal interactions as the primary mechanism for the formation of hot Jupiters (e.g., Triaud et al. 2010; Winn et al. 2010).

Planets formed at a few AU’s are scattered to the proximity of their host stars when their eccentricities approach unity. Their orbits may be circularized by subsequent tidal dissipation in the planets but its efficiency depends sensitively on the distance of closest approach (e.g., Ivanov & Papaloizou 2004). Dynamical relaxation generally leads to a Rayleigh distribution in eccentricity (Zhou et al. 2007). If this process is the leading cause for planets to venture into their stellar proximity, its combined effect with the tidal circularization process would yield a continuous periastron distribution (Zhang et al. 2010, in preparation), which is not consistent with the observed sharply bimodal distribution.

Current data suggest that there may be two populations of short-period exoplanet systems, one with spin-orbit alignment, the other with significant misalignment (Schlaufman 2010; Winn et al. 2010). Although stellar or planetary companions have been identified as potential culprits for Kozai mechanism to operate in some systems, it may not be the dominant process to account for the origin of many hot Jupiters which do not appear to be either bound to binary stars or associated with planetary siblings with comparable masses and periods less than a decade.

The solar system also provides a clue. Except for Pluto, all planets outside 1 AU lie within 2° of the ecliptic plane, while the Sun’s equatorial plane is inclined by 7° with respect to the ecliptic. There is no obvious celestial candidate which can impose sufficient secular perturbation to induce this observed spin-orbit inclination.

We note that spin-orbit misalignment is not limited to planetary systems. Hale (1994) has measured the inclination to the line of sight of the spins of stars in binaries by comparing the rotational period to the $v \sin i$ values of rotationally broadened lines, and inferred that binaries are spin-aligned for $a \lesssim 30-40$ AU, but become randomly oriented for larger orbits. A particularly striking example is the binary system DI Herculis: Both stars rotate with their spin axes nearly perpendicular to the orbital axis and inclined to each other (Albrecht et al. 2009). Recently, a number of close binaries (with period of a few days) have been found to have nonzero stellar obliquities (A. Triaud, J. Winn, private communications, 2010).

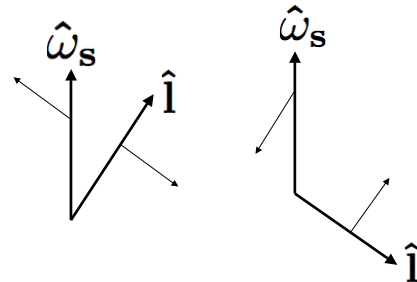


Figure 1. A sketch of the effect of the magnetic warping torque. This torque tends to push the disc angular momentum axis \hat{l} toward a state perpendicular to the spin axis $\hat{\omega}_s$. When \hat{l} is fixed by the outer disc, the back reaction torque tends to push the spin axis toward being misaligned with \hat{l} .

1.2 This Paper

In this paper and the companion paper (Foucart & Lai 2010, hereafter Paper II), we explore an alternative scenario for the observed spin-orbit misalignment in exoplanet and binary star systems. We assume that the planets’ present-day orbits are in the plane of their natal discs. We study the mutual interaction between a magnetic young star and its surrounding disc, and show that under certain (but realistic) conditions, the stellar spin axis can be pushed away from the disc axis toward the perpendicular state and even the retrograde state. Planets formed in the disc therefore may have their orbital axes misaligned with the stellar spin axis, even before any additional planet-planet scatterings or Kozai interactions take place. The basic idea is the following. A magnetic protostar (with $B_\star \gtrsim 10^3$ G, typical for classical T Tauri stars; see, e.g., Bouvier et al. 2007; Donati & Landstreet 2009) generally exerts a warping torque and a precessional torque on the inner region disc before the disc is disrupted at the magnetosphere boundary (Section 2; see Lai 1999). These torques have a tendency to make the inner disc tilt away from the stellar spin axis and precess around it on a warping timescale, which is much longer than the rotation period (see Fig. 3 below for a simple “laboratory” toy model that explains the origin of the warping torque)². However, internal processes in the disc will try to resist the inner disc warping, either by viscous stress or by bending wave propagation. The result is that, for the reasonable disc/stellar parameters, the inner disc may not be significantly warped (see Paper II), i.e., the direction of the inner disc is approximately aligned with that of the outer disc (assumed to be fixed; but see below). The back-reaction torque

² Note that the secular disc warp discussed in this paper is different from the dynamical warp which varies on the timescale of the stellar rotation period. Such dynamical warp may arise from the periodic vertical force on the disc from the magnetic star (Terquem & Papaloizou 2000; Lai & Zhang 2008), or from the simple effect where the disc material “climbs” up the field lines at the magnetosphere boundary before funneling to the magnetic polar cap [see Bouvier et al. (2007) for possible observational evidence of dynamical warps in the classical T Tauri star AA Tauri]. The dynamical disc warp averages to zero over an rotation period and has no effect on the secular evolution of the system.

will then act on the star, changing the spin direction on a timescale much longer than the disc warping time. Thus, even if initially the stellar spin axis is approximately (but not perfectly) aligned with the disc axis, given enough time, the stellar spin axis will evolve towards the perpendicular state and even the retrograde state (see Fig. 1). Therefore, a young planet, formed with its orbit axis aligned with disc axis, may be misaligned with the stellar spin axis.

While the magnetic warping torque alone pushes the stellar spin towards misalignment, other torques (such as that due to the angular momentum carried by the accreting gas) tend to align the stellar spin with the disc axis. When these torques are included, the misalignment effect is reduced. However, we show that with reasonable disc parameters, the warping torque could still be dominant and spin-disc misalignment can be (but not always) produced under general conditions.

We note that even without the magnetic effect discussed above, misalignment between stellar spin and disc axis could be a natural consequence of star formation process itself. Indeed, when stars form under the turbulent conditions of molecular clouds, the gas accreting onto the protostar does not necessarily fall in with a fixed orientation (e.g., McKee & Ostriker 2007), i.e., the outer disc direction can vary in time. Additionally, the disc can be perturbed by other nearby stars and change orientation (e.g., Bate et al. 2003; Pfalzner et al. 2005). If the stellar spin is determined by the total angular momentum gained over its whole formation history, while the orbit of a planet is coplanar with the accretion disc towards the end of its evolution, then spin-orbit misaligned planetary systems may be produced (Bate et al. 2010). However, since the gas disc carries a large amount of angular momentum, one might expect that efficient spin-orbit alignment will be achieved in the absence of any magnetic interaction. Thus, in this picture, it is important to understand how the stellar spin evolves and on what timescale (and whether this timescale is shorter or longer than the timescale of varying outer disc orientation).

The remainder of this paper is organized as follows. In Sect. 2, we present an analytical model used to describe the interaction between a magnetic star and its disc, and derive the magnetic torques acting on the disc. This is similar to the model considered in Lai (1999), but takes into account of more recent works on magnetosphere – disc interactions. In Sect. 3 we qualitatively discuss disc warp due to the magnetic torques, relegating technical details to Paper II. We then study in Sect. 4 the evolution of stellar spin axis due to the back-reactions of the magnetic warping torque and other torques, under the assumption that the disc is approximately flat. In Sect. 5 we apply our theory to the problem of spin-orbit misalignment in exoplanetary systems and present two possible scenarios that may play a role in explaining the observations. Finally we discuss the implications of our results in Sect. 6.

2 ANALYTIC MODEL OF MAGNETIC STAR – DISC INTERACTION: DISC WARPING TORQUE

The interaction between a magnetic star and its circumstellar disc has been studied over many decades, both theoret-

ically (e.g., Pringle & Rees 1972; Ghosh & Lamb 1979; Aly 1980; Wang 1987; Aly & Kuijpers 1990; Shu et al. 1994; van Ballegoijen 1994; Lovelace et al. 1995, 1999; Lai 1999; Uzdensky et al. 2002; Pfeiffer & Lai 2004; D’Angelo & Spruit 2010) and using numerical simulations (e.g., Hayashi et al. 1996, 2000; Miller & Stone 1997; Goodson et al. 1997; Fendt & Elstner 2000; Matt et al. 2002; Romanova et al. 2003, 2009). Most previous works deal with the case where the stellar spin axis, the magnetic axis and the disc axis are aligned. Even for such a “simple” case, the problem is complex. There are at least four physical ingredients involved in the magnetosphere – disc interaction: (i) The stellar magnetic field penetrates through part of the disc, establishing magnetic linkage between the star and the disc. This may be achieved either through dissipation in the disc (if the disc is sufficiently dissipative) or, more likely, through reconnection between the stellar and disc fields – the latter may be associated with dynamo actions in the disc. (ii) In the inner disc regions where ionization fraction is non-negligible, magnetic fields diffuse through the disk on a time scale much longer than the orbital period (e.g., Shu et al. 2008; Terquem 2008). In this case, the field lines linking the star and the disc are twisted because of the difference in the stellar rotation ω_s and disc rotation $\Omega(r)$, generating toroidal fields ΔB_ϕ from the vertical field B_z that threads the disc. After a characteristic time of order $|\omega_s - \Omega(r)|^{-1}$, the toroidal field $|\Delta B_\phi|$ becomes comparable to $|B_z|$, and the flux tube starts expanding at a fast rate and the fields open up, temporarily disconnecting the star – disc linkage (e.g., Aly 1985; Aly & Kuijpers 1990; van Ballegoijen 1994; Lynden-Bell & Boily 1994; Lovelace et al. 1995). However, reconnection between the inflated field lines relaxes the shear and restore the linkage between the star and the disc, and the whole cycle repeats (Aly & Kuijpers 1990; van Ballegoijen 1994; Goodson et al. 1997; Matt et al. 2002)³. (iii) Some open field lines are strongly “pinched” and twisted by the conducting disc, leading to a conical wind from a localized region near the magnetosphere–disc boundary which carries away angular momentum from the accreting gas (e.g., Shu et al. 1994; Romanova et al. 2009). (iv) In the open field line region near the stellar rotation axis, outflows could be launched, carrying away angular momentum from the star (e.g., Matt & Pudritz 2005). Even without significant mass loss, angular momentum may be transferred outwards through Alfvén waves.

All these four processes are likely to play a role in the spin evolution of the protostar. Obviously, for the general case where the stellar spin axis, magnetic axis and disc axis are misaligned, the situation is even more complicated. Moreover, the magnetic warping and spin-orbit misalignment considered in this paper take place on timescales much longer than the dynamical time (i.e., the spin period or disc orbital period), and therefore cannot be easily captured in 3D numerical simulations.

Nevertheless, the key physical effects of the magnetic star – disc interaction relevant to this paper can be described robustly in a parametrized manner (Lai 1999; see

³ Strictly steady-state models have also been considered, but they generally require special conditions for the disc (see Uzdensky 2004 and references therein).

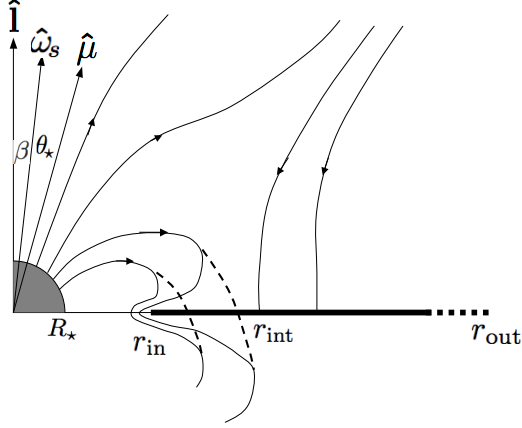


Figure 2. A sketch of magnetic field configuration in a star – disc system for nonzero β (the angle between the disc axis and the stellar spin axis) and θ_* (the angle between the stellar dipole axis and the spin axis). Part of the stellar magnetic fields (dashed lines) penetrate the disc in the interaction zone between the disc inner radius r_{in} and r_{int} in a cyclic manner, while other field lines are screened out of the disc. The closed field lines are twisted by the differential rotation between the star and the disc, which leads to a magnetic braking torque and a warping torque. The screening current in the disc leads to a precessional torque.

Fig. 2). The stellar magnetic field disrupts the accretion flow at the magnetospheric boundary. Some of the accreting gas are channelled onto the polar caps of the star while other gas could be ejected in an outflow. The magnetosphere boundary is located where the magnetic and plasma stresses balance. For a dipole field, the inner disc radius is

$$r_{\text{in}} = \eta \left(\frac{\mu^4}{GM_* \dot{M}} \right)^{1/7}, \quad (1)$$

where M_* and μ are the mass and magnetic dipole moment of the central star, \dot{M} is the mass accretion rate, and η is a dimensionless constant of order unity, with typical estimates ranging from 0.5 to 1 and recent numerical simulation giving $\eta \sim 0.5$ (e.g., Long et al. 2005). Before being disrupted, the disc generally experiences magnetic torques from the star. The vertical (perpendicular to the disc) magnetic field produced by the stellar dipole is given by

$$B_z = -\frac{\mu}{r^3} (\cos \theta_* \cos \beta - \sin \theta_* \sin \beta \sin \omega_s t), \quad (2)$$

where θ_* is the angle between the magnetic dipole axis $\hat{\mu}$ and the spin axis $\hat{\omega}_s$, and β is the angle between $\hat{\omega}_s$ and the disc axis \hat{l} (see Fig. 2) (note that for a warped disc, \hat{l} depends on r). We assume that the static field component, $B_z^{(s)} = -(\mu/r^3) \cos \theta_* \cos \beta$, penetrates the disc in an “interaction zone”, between r_{in} and r_{int} . As discussed before, this field is twisted by the differential rotation between the star and the disc, undergoing cycles of field inflation and reconnection. The differential rotation generates toroidal field, whose value at near the disc increases in time until it becomes comparable to $|B_z^{(s)}|$, at which point reconnection reduces the field twist, and then the cycle repeats. We parameterize the averaged value of the toroidal field generated by the twist by

$$\Delta B_\phi = \mp \zeta B_z^{(s)}, \quad (3)$$

where the upper/lower sign refers to the value above/below the disc plane, and $|\zeta| \sim 1$ (e.g., Aly 1985; van Ballegoijen 1994; Lynden-Bell & Boily 1994; Lovelace et al. 1995). The sign of ζ is such that $\zeta > 0$ for $\Omega(r) - \omega_s \cos \beta > 0$, and $\zeta < 0$ for $\Omega(r) - \omega_s \cos \beta < 0$. Note that near the corotation radius, $\Omega = \omega_s \cos \beta$, the toroidal field may be limited by field diffusion inside the disc. Thus, $|\Delta B_\phi/B_z| \sim |\Omega - \omega_s \cos \beta| \tau \lesssim 1$ near the corotation radius, where τ is the field dissipation timescale for the toroidal field in the disc. However, such region is very small and can be neglected, and we will adopt Eq. (3) throughout this paper. The twisted toroidal field (3) implies a radial surface current $K_r = (c/2\pi)\zeta B_z^{(s)}$. The vertical field $B_z^{(s)}$ acts on K_r , giving rise to an azimuthal force on the disc material and a (well-known) magnetic braking torque (per unit area)

$$\mathbf{N}_{\text{mb}} = -\frac{\zeta}{2\pi} r |B_z^{(s)}|^2 \hat{l}. \quad (4)$$

This torque exists even for the aligned case. For $\beta \neq 0$, however, there exists an additional torque: The interaction between K_r and the toroidal component of the dipole field, $B_\phi^{(\mu)} = -(\mu/r^3)(\hat{\mu} \cdot \hat{\phi})$ (where $\hat{\phi}$ is the unit vector in the azimuthal direction), gives rise to a vertical force on the disc:

$$F_z = \frac{1}{8\pi} [(B_\phi^{(\mu)} + \zeta B_z^{(s)})^2 - (B_\phi^{(\mu)} - \zeta B_z^{(s)})^2] = \frac{\zeta}{2\pi} B_\phi^{(\mu)} B_z^{(s)}. \quad (5)$$

After averaging over the azimuthal angle in the disc and the stellar rotation period, the net torque (per unit area) on the disc is

$$\mathbf{N}_w = -\frac{\zeta \mu^2}{4\pi r^5} \cos \beta \cos^2 \theta_* \hat{l} \times (\hat{\omega}_s \times \hat{l}). \quad (6)$$

For $\zeta > 0$ (i.e., inside the corotation radius), the effect of this torque (for a fixed spin axis $\hat{\omega}_s$) is to push the disc axis \hat{l} away from $\hat{\omega}_s$ toward the “perpendicular” state (see Fig. 1). The characteristic warping rate is (for $\beta \sim 0$)

$$\Gamma_w(r) = \frac{\zeta \mu^2}{4\pi r^7 \Omega(r) \Sigma(r)} \cos^2 \theta_*, \quad (7)$$

where $\Sigma(r)$ is the surface density of the disc. Note that in the case of $\beta = \theta_* = 0$, the corotation radius r_{co} (where $\Omega = \omega_s$) is somewhat larger than r_{in} for stars in the spin equilibrium (e.g., the simulation by Long et al. 2005 indicates that $r_{\text{co}}/r_{\text{in}}$ lies in the range of 1.2-1.5). Thus, for the inner region of the disc most relevant to our paper, the condition $\zeta > 0$ is satisfied.

The warping torque also exists for more complex stellar magnetic fields, which may be present for accreting T Tauri stars (e.g., Hussain et al. 2009; Donati et al. 2010). Consider an axisymmetric quadrupole field with the symmetric axis along $\hat{\mathbf{Q}}$ (the 3rd axis) such that the magnetic quadrupole moment tensor satisfies $Q_{11} = Q_{22} = -Q_{33}/2 \equiv -Q/2$. Outside the star, the stellar quadrupole field is given by

$$\mathbf{B}_Q = \frac{3Q}{4r^4} [5(\hat{\mathbf{Q}} \cdot \hat{\mathbf{r}})^2 - 1] \hat{\mathbf{r}} - \frac{3Q}{2r^4} (\hat{\mathbf{Q}} \cdot \hat{\mathbf{r}}) \hat{\mathbf{Q}}. \quad (8)$$

Again, we assume that the static component of the vertical field, $B_{Q,z}^{(s)} = -(3Q/4r^4)(3 \cos^2 \theta_Q - 1) \sin \beta \cos \beta \sin \phi$ (where θ_Q is the angle between $\hat{\omega}_s$ and $\hat{\mathbf{Q}}$), penetrates through the disc in a finite region between r_{in} and r_{int} , and gets twisted to produce $\Delta B_\phi = \mp \zeta B_{Q,z}^{(s)}$. After azimuthal

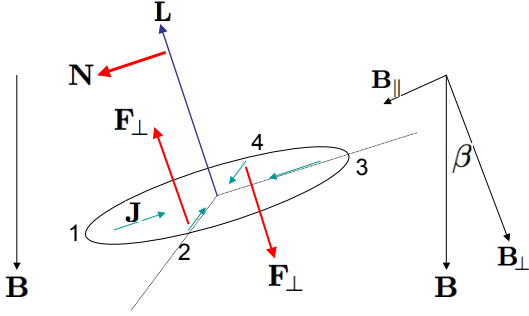


Figure 3. A toy model for understanding the origin of the warping torque. A tilted rotating metal plate (with angular momentum \mathbf{L}) in an external magnetic field \mathbf{B} experiences a vertical magnetic force around region 2 and 4 due to the interaction between the induced current \mathbf{J} and the external \mathbf{B}_{\parallel} , resulting in a torque \mathbf{N} which further increases the tilt angle β .

averaging and time averaging over the stellar rotation, we find the warping torque due to the quadrupole field:

$$\mathbf{N}_w^{(Q)} = -\frac{9\zeta Q^2}{128\pi r^7} (3\cos^2\theta_Q - 1)^2 \sin^2\beta \cos\beta \hat{\mathbf{l}} \times (\hat{\omega}_s \times \hat{\mathbf{l}}). \quad (9)$$

Thus, this torque has the same qualitative effect as the warping torque due to the magnetic dipole. For simplicity, we will neglect $\mathbf{N}_w^{(Q)}$ in the remainder of this paper.

We note that the existence of the warping torque is rather robust. The two basic ingredients are: (i) Magnetic field lines from the star penetrate the inner disc which rotates faster than the star; (ii) the connected field lines are twisted, reaching a quasi-steady twist angle. Both ingredients involve dissipations. Qualitatively speaking, the warping torque tends to push the system toward the perpendicular state (with the disc axis perpendicular to stellar spin) in order to minimize the energy associated with the twisted magnetic fields. In fact, the essential physics of the warping torque is captured by the following “laboratory” toy model (cf. Lai 2003), depicted in Fig. 3: Consider a metal plate (not a perfect conductor) in an external uniform magnetic field \mathbf{B} , with the plate surface initially perpendicular to \mathbf{B} . Neglect gravity. When the plate rotates (due to some external torque) with the rotation axis \mathbf{L} , an EMF is induced (in the direction of $\mathbf{v} \times \mathbf{B}$) and a radial current \mathbf{J} generated in the plate – this is the same surface current K_r mentioned before eq. (4). The interaction between \mathbf{J} and \mathbf{B} gives rise to a “magnetic braking” torque which tends to slow down the plate’s rotation. Now tilt the plate by an angle β (and keep the plate rotating). The interaction between \mathbf{J} and \mathbf{B}_{\parallel} (the component of \mathbf{B} parallel to the plate) produces a vertical force around region 2 and region 4 in the plate. The result is a torque \mathbf{N} which tends to push the plate’s rotation axis \mathbf{L} away from the magnetic direction, further increasing the tilt.

In addition to the warping torque, there is also a precessional torque on the disc when $\beta \neq 0$. This arises from the dielectric property of the disc: If the disc does not allow the vertical stellar field (e.g., the rapidly varying component of B_z due to stellar rotation) to penetrate, an azimuthal screening current K_ϕ will be induced in the disc. This K_ϕ

interacts with the radial magnetic field B_r from the stellar dipole and produces a vertical force. After azimuthal averaging and averaging over the stellar rotation, we obtain the torque per unit area:⁴

$$\mathbf{N}_p = -\frac{\mu^2}{\pi^2 r^5 D(r)} \sin^2\theta_* \cos\beta \hat{\omega}_s \times \hat{\mathbf{l}}, \quad (10)$$

where the dimensionless function $D(r)$ is given by

$$D(r) = \max \left(\sqrt{r^2/r_{\text{in}}^2 - 1}, \sqrt{2H(r)/r_{\text{in}}} \right), \quad (11)$$

and $H(r)$ is the half-thickness of the disc. The torque (10) tends to make the disc precess around the stellar spin axis.

3 WARPED DISCS

As shown in Sect. 2, the inner region of the disc where magnetic field lines connect star and the disc and where the disc rotates faster than the star ($\Omega > \Omega_s \cos\beta$) experiences a warping torque and a precessional torque. If we imagine dividing the disc into many rings, and if each ring were allowed to behave independent of each other, it would be driven toward a perpendicular state ($\hat{\mathbf{l}} \perp \hat{\omega}_s$) and precess around the spin axis of the central star. Obviously, real protoplanetary discs do not behave as a collection of non-interacting rings: Hydrodynamic force and viscous force provide strong couplings between different rings. Depending on the physical condition of the disc, the dynamics of a warped disc may be driven by viscous diffusion (when the viscous α -parameter is greater than the dimensional disc thickness H/r) or propagation of bending waves (when $\alpha \lesssim H/r$) (Papaloizou & Pringle 1983; Paper II).

Thus, for a given outer disc direction $\hat{\mathbf{l}}_{\text{out}}$ and stellar spin axis $\hat{\omega}_s$, the disc will generally evolve into a warped state, with $\hat{\mathbf{l}}$ dependent on r . In particular, the orientation of the disc at the inner radius, $\hat{\mathbf{l}}_{\text{in}} = \hat{\mathbf{l}}(r_{\text{in}})$, generally differs from $\hat{\mathbf{l}}_{\text{out}}$. For typical protostar parameters, $M_* \sim 1 M_\odot$, $R_* \sim 2R_\odot$, $\mu = B_* R_*^3$ (with the surface field $B_* \sim 10^3$ G), and mass accretion rate $\dot{M} \sim 10^{-8} M_\odot \text{ yr}^{-1}$, the inner disc is located at a few stellar radii. From equation (7), we find that the timescale for the warp evolution is of order

$$\Gamma_w^{-1} = (92 \text{ days}) \left(\frac{1 \text{ kG}}{B_*} \right)^2 \left(\frac{2R_\odot}{R_*} \right)^6 \left(\frac{M_*}{1 M_\odot} \right)^{1/2} \times \left(\frac{r}{8R_\odot} \right)^{11/2} \left(\frac{\Sigma}{10 \text{ g cm}^{-2}} \right) (\zeta \cos\theta_*)^{-1}. \quad (12)$$

As shown in Paper II, under the combined actions of warping/precessional torques and disc viscosity or bending waves, the disc will settle down into a steady state on a timescale that depends on disc viscosity and sound speed [see related work by Papaloizou & Terquem (1995) for discs in binary stars with inclined orbits.] In general, this timescale can be up to several orders of magnitude of Γ_w^{-1} evaluated at r_{in} . Nevertheless, it is much shorter than the disc lifetime and the timescale of the secular evolution of the stellar spin (see Eq. 14 below). Moreover, we show in Paper II that

⁴ This assumes that only the spin-variable vertical field is screened out by the disc. If the vertical field is entirely screened out, then $(-\sin^2\theta_*)$ should be replaced by $(2\cos^2\theta_* - \sin^2\theta_*)$.

for most reasonable stellar/disc parameters, the steady-state disc warp is rather small because of efficient viscous damping or propagation of bending waves. Thus, we will adopt the approximation $\hat{\mathbf{l}}(r) \simeq \hat{\mathbf{l}}_{\text{out}}$ in the remainder of this paper, leaving more detailed study of the effect of warped discs to Paper II.

4 SECULAR EVOLUTION OF STELLAR SPIN

We now consider the evolution of the stellar spin direction due to the back-reaction of the magnetic warping torque and other torques. Note that we are interested in the long-term evolution of the stellar spin. The specific angular momentum of the accreting gas at r_{in} is given by the Keplerian value $\sqrt{GM_* r_{\text{in}}}$, so the characteristic accretion torque on the star is

$$\mathcal{N}_0 = \dot{M}(GM_* r_{\text{in}})^{1/2}. \quad (13)$$

Thus the fiducial timescale for the spin evolution is

$$t_{\text{spin}} = \frac{J_s}{\mathcal{N}_0} = (1.25 \text{ Myr}) \left(\frac{M_*}{1 M_\odot} \right) \left(\frac{\dot{M}}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-1} \times \left(\frac{r_{\text{in}}}{4R_*} \right)^{-2} \frac{\omega_s}{\Omega(r_{\text{in}})}, \quad (14)$$

where we have assumed the stellar spin angular momentum $J_s = 0.2M_* R_*^2 \omega_s$ (for a fully convective protostar modeled as a $\Gamma = 5/3$ polytrope).

In general, the evolution equation for the spin angular momentum of the star, $J_s \hat{\omega}_s$, can be written in the form

$$\frac{d}{dt} (J_s \hat{\omega}_s) = \mathcal{N} = \mathcal{N}_l + \mathcal{N}_s + \mathcal{N}_w + \mathcal{N}_p. \quad (15)$$

Here \mathcal{N}_l represents the torque component that is aligned with the inner disc axis $\hat{\mathbf{l}}_{\text{in}}$ ($= \hat{\mathbf{l}}$ for a flat disc):

$$\mathcal{N}_l = \lambda \dot{M} (GM_* r_{\text{in}})^{1/2} \hat{\mathbf{l}}, \quad (16)$$

where λ is a dimensionless parameter. Equation (16) includes not only the accretion torque carried by the accreting gas onto the star, $\dot{M}_{\text{acc}} (GM_* r_{\text{in}})^{1/2} \hat{\mathbf{l}}$ (note that in general, the accretion rate onto the star, \dot{M}_{acc} , may be smaller than \dot{M} , the disc accretion rate), but also includes the magnetic braking torque associated with the disc – star linkage, as well as any angular momentum carried away by the wind from the magnetosphere boundary. While the details are complex, we would expect that all these contributions to \mathcal{N}_l tend to make $\lambda < 1$, as suggested by recent numerical simulations (e.g., Romanova et al. 2009) and earlier works (e.g., Shu et al. 1994). The term $\mathcal{N}_s = -|\mathcal{N}_s| \hat{\omega}_s$ represents a spindown torque carried by a wind/jet from the open field line region of the star. In the aligned case ($\hat{\mathbf{l}} = \hat{\omega}_s$) studied by previous works, \mathcal{N}_l and \mathcal{N}_s are the only torques acting on the star, and spin equilibrium is reached when $\lambda \dot{M} (GM_* r_{\text{in}})^{1/2} = |\mathcal{N}_s|$. Note that in general, the values of λ and \mathcal{N}_s may depend on β and other quantities.

The term \mathcal{N}_w and \mathcal{N}_p represent the back-reactions of the warping and precessional torques, respectively. From

Eq. (6), we have

$$\begin{aligned} \mathcal{N}_w &= - \int_{r_{\text{in}}}^{r_{\text{int}}} 2\pi r \mathbf{N}_w dr \\ &= \frac{\zeta' \mu^2}{6r_{\text{in}}^3} \cos^2 \theta_* \cos \beta \hat{\mathbf{l}} \times (\hat{\omega}_s \times \hat{\mathbf{l}}) \\ &= \mathcal{N}_0 n_w \hat{\mathbf{l}} \times (\hat{\omega}_s \times \hat{\mathbf{l}}), \end{aligned} \quad (17)$$

where

$$n_w = \frac{\zeta'}{6\eta^{7/2}} \cos^2 \theta_* \cos \beta, \quad (18)$$

with⁵

$$\zeta' = \zeta [1 - (r_{\text{in}}/r_{\text{int}})^3]. \quad (19)$$

Similarly, from Eq. (10), we have

$$\mathcal{N}_p = - \int_{r_{\text{in}}}^{\infty} 2\pi r \mathbf{N}_p dr = \mathcal{N}_0 n_p \hat{\omega}_s \times \hat{\mathbf{l}}, \quad (20)$$

with (for thin discs)⁶,

$$n_p = \frac{4}{3\pi\eta^{7/2}} \sin^2 \theta_* \cos \beta. \quad (21)$$

Note that both \mathcal{N}_w and \mathcal{N}_p are of order μ^2/r_{in}^3 (see the first line of Eq. [17]), which does not directly depend on \dot{M} . However, when we use Eq. (1) for r_{in} , we find that both \mathcal{N}_w and \mathcal{N}_p are of the same order of magnitude as the fiducial accretion torque \mathcal{N}_0 . Therefore, as we will see below, the timescale to change the stellar spin direction (if at all) is of the same order as t_{spin} .

From Eq. (15), we find that the magnitude of the stellar spin evolves according to

$$\frac{d}{dt} J_s = \mathcal{N} \cdot \hat{\omega}_s = \mathcal{N}_0 (\lambda \cos \beta + n_w \sin^2 \beta) - |\mathcal{N}_s|. \quad (22)$$

The inclination angle of the stellar spin relative to the disc evolves according to the equation

$$\frac{d}{dt} \cos \beta = \frac{\mathcal{N}_0}{J_s} \sin^2 \beta (\lambda - \tilde{\zeta} \cos^2 \beta), \quad (23)$$

where

$$\tilde{\zeta} = \frac{\zeta' \cos^2 \theta_*}{6\eta^{7/2}}. \quad (24)$$

Equation (23) is the key result of this paper. Note that while \dot{J}_s depends on the (unspecified) spin-down torque $|\mathcal{N}_s|$, the evolution of the spin-orbit inclination angle β depends only on two dimensionless parameters: λ and $\tilde{\zeta}$. Although the precise values of these two parameters are uncertain (see Sect. 2), we expect λ to lie in the range of 0.1 – 1, and $\tilde{\zeta}$ to range from somewhat less unity to a few (for $\zeta' \simeq \zeta \sim 1$ and $\eta \simeq 0.5$).

Equation (23) reveals the following behavior for the evolution of β (see Fig. 4):

(i) For $\lambda = 0$, equation (23) describes the effect of the magnetic warping torque acting alone on the star. This torque always pushes the stellar spin toward anti-alignment

⁵ This expression for ζ' assumes that the corotation radius r_{co} is larger than r_{int} .

⁶ The coefficient $\frac{4}{3}$ in equation (21) is only valid in the limit $\delta = H/r \rightarrow 0$. For small but finite δ , we get $\frac{4}{3}[1 - \frac{3}{2}\sqrt{\frac{\delta}{2}} + O(\delta)]$.

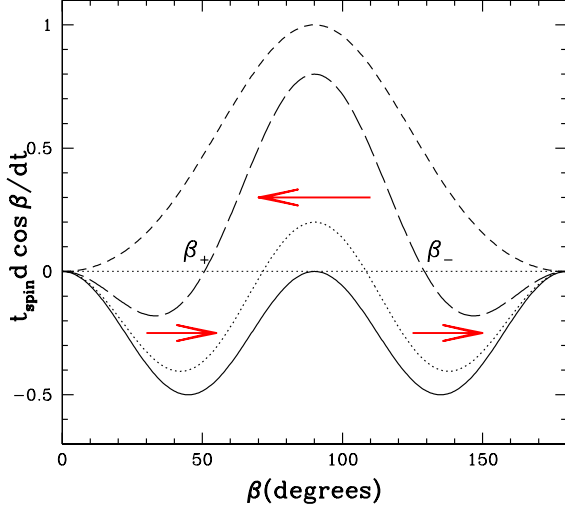


Figure 4. The rate of change of the stellar inclination angle β for a fixed disc rotation axis (see Eq. 23). From top to bottom, the four curves correspond to $(\lambda, \tilde{\zeta}) = (1, 0.5)$, $(0.8, 2)$, $(0.2, 2)$ and $(0, 2)$, respectively. The arrows indicate the direction of β evolution. For $\tilde{\zeta}/\lambda < 1$, the stellar spin evolves towards alignment for all β (see the short-dashed line); for $\tilde{\zeta}/\lambda > 1$, the spin either evolves toward $\beta_+ \neq 0$ or toward anti-alignment ($\beta = 180^\circ$), depending on the initial values of β . The fiducial spin evolution timescale t_{spin} is defined in Eq. (14).

with \hat{l} (see Fig. 1). In particular, the aligned state ($\beta = 0$) is unstable: For $\beta \ll 1$, we have $\dot{\beta}/\beta = \tilde{\zeta}/t_{\text{spin}}$. On the other hand, the perpendicular state ($\beta = \pi/2$) represents a “bottleneck” where the warping torque \mathcal{N}_w vanishes: For $\beta = \pi/2 + \Delta$ with $|\Delta| \ll 1$, we have $\dot{\Delta}/\Delta \simeq (\tilde{\zeta}/t_{\text{spin}})\Delta$. Thus, when the outer disc orientation is fixed (see Section 5), starting from a small β , it would take infinite time to cross this 90° barrier.

(ii) For $\tilde{\zeta}/\lambda < 1$: Regardless of the initial β , the spin always evolves towards alignment.

(iii) For $\tilde{\zeta}/\lambda > 1$: There are two possible directions of β evolution, depending on the initial value of β . The condition $d \cos \beta / dt = 0$ yields two “equilibrium” states (β_+ and β_-), given by

$$\cos \beta_{\pm} = \pm \sqrt{\lambda/\tilde{\zeta}}. \quad (25)$$

Of the two equilibria, one is stable (β_+) and the other is unstable. For $\beta(t=0) < \beta_-$, the system will evolve towards a misaligned prograde state β_+ ; for $\beta(t=0) > \beta_-$, the system will evolve towards the anti-aligned state ($\beta = 180^\circ$).

Note that the timescale to change the stellar spin (Eq. [14]) can be written as $t_{\text{spin}} = (J_s/M_\star l_{\text{in}})(M_\star/\dot{M})$, where $l_{\text{in}} = \sqrt{GM_\star r_{\text{in}}}$ is the specific angular momentum of the accreting gas at r_{in} . The disk lifetime (observed to be around 10 Myrs) is a few times less than M_\star/\dot{M} if one uses the appropriately averaged value of \dot{M} . Since $J_s/(M_\star l_{\text{in}}) \ll 1$, this implies that t_{spin} is typically less than the disk lifetime, i.e., significant change of the stellar spin can be achieved during the disk lifetime. Of course, in the earlier phases of the protostars (e.g., Class-0 T Tauri, with $\dot{M} \sim 10^{-5} M_\odot/\text{yr}$), t_{spin} is much shorter than 1 Myrs, while in the later phases t_{spin} is longer.

5 APPLICATION TO SPIN-ORBIT MISALIGNMENT IN EXOPLANETARY SYSTEMS

The results of previous sections clearly show that, contrary to the standard assumption, the spin axis of a magnetic protostar does not necessarily align with the axis of its circumstellar disc. Therefore, a planet formed in the disc may have its orbital axis misaligned with the stellar spin, even before any few-body interactions (such as strong planet-planet scatterings and Kozai interactions) take place. A clear prediction of the expected spin-orbit misalignment angle and its distribution for an ensemble of planetary systems is complicated by the fact that the physics of magnetic star – disc interaction is complex: Even with our general parameterized model, the evolution of β depends on two unknown dimensionless parameters ($\lambda, \tilde{\zeta}$). The final misalignment angle and its distribution also depend on the usual parameters associated with protoplanetary discs (such as the accretion rate and lifetime), as well as on the initial conditions for the disc direction relative to the stellar spin.

We now discuss two scenarios to illustrate the possible outcomes for the spin-orbit misalignment angles in exoplanetary systems.

5.1 Scenario (a)

Here we consider the case where the collapsing/accreting materials that form the protostar and its disc all have angular momentum axes approximately in the same direction. This would lead to an initial state where the stellar spin and the disc axis are approximately aligned (with small β). As we showed in Sect. 4, for systems with $\tilde{\zeta}/\lambda < 1$, the angle β will decrease and the spin-orbit alignment will be enhanced. For systems with $\tilde{\zeta}/\lambda > 1$, however, the angle β will increase towards β_+ (see Fig. 4).

In the idealized situation where the disc axis \hat{l} is fixed in time, we would expect that some planetary systems to have β close to zero, while others to have β clustered around values somewhat less than β_+ . Since $\beta_+ = \cos^{-1} \sqrt{\lambda/\tilde{\zeta}}$ are different for different systems, we may not expect a strong clustering. Note that because β_+ is always less than 90° , no planet in a retrograde orbit can be produced in this idealized situation. However, if we consider the possibility that the axis of the outer disc changes in time – as might be expected because the gas that feeds the outer disc does not necessarily have a fixed rotation axis or because the outer disc is perturbed by a distant star in a cluster, then planets on retrograde orbits may be produced. To achieve this, the outer disc axis must vary with sufficient amplitude [larger than $(\beta_- - \beta_+)$] and on sufficiently short timescale (shorter than the spin evolution time), and the inner disc axis must adjust (via bending wave propagation or viscous diffusion) quickly to the variation of the outer disc, so that a system at the $\beta < \beta_+$ state may be pushed over to the $\beta > \beta_-$ state — We will show in Paper II that this is possible.

5.2 Scenario (b)

Here we consider the case where the initial stellar spin axis and the disc axis are randomly distributed with respect to each other. This might be expected if the turbulent gas in

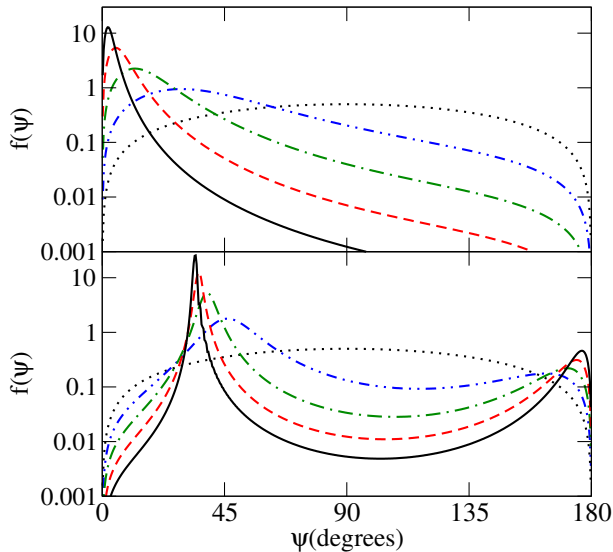


Figure 5. Distribution of the angle ψ between the stellar rotation axis and the disc axis at $t/t_{\text{spin}} = 0$ (dotted line), 1, 2, 3, 4 (solid line), for $\tilde{\zeta} = 0.125$ (upper panel) and $\tilde{\zeta} = \sqrt{2}$ (lower panel), both with $\lambda = 1$. The initial distribution is isotropic.

a molecular cloud core that feeds into the disc falls in with random directions. Suppose at the time of planetary formation, the stellar spin is determined by the accumulative angular momentum accretion, then the stellar spin axis may be quite different from the “current” disc axis (e.g., Bate et al. 2009), and the distribution of the spin-orbit misalignment angle may be quite broad. The important problem that we wish to address here is: How the distribution function $f(\psi, t)$ evolves further in time? (Here we define the angle between $\hat{\mathbf{l}}$ and $\hat{\boldsymbol{\omega}}_s$ as $\psi = \beta$, in agreement with the notation used in observational papers; see Triaud et al. 2010).

Without the magnetic warping effect discussed in Sect. 4, the systems will evolve toward alignment, therefore an initial random distribution, $f(\psi, 0) = \sin \psi / 2$, will become increasingly more peaked towards $\psi < 90^\circ$ as time passes. However, when the magnetic warping effect is taken into account, a variety of outcomes become possible, as it is clear from our results in Sect. 4.

Consider a simple model where λ , $\tilde{\zeta}$ and t_{spin} are constant in time and the same for different systems. Then the evolution of $f(\psi, t)$ is governed by the equation

$$\frac{\partial}{\partial t} f(\psi, t) = -\frac{\partial}{\partial \psi} \left[f(\psi, t) \frac{d}{dt} \psi \right], \quad (26)$$

where the time derivative of $\psi = \beta$ is given by Eq. (23). In Fig. 5, we plot $f(\psi, t)$ between $t = 0$ and $t = 4t_{\text{spin}}$ for $(\lambda, \tilde{\zeta}) = (1, 0.125)$ and $(1, \sqrt{2})$, assuming an initial isotropic distribution $f(\psi, 0) = (\sin \psi) / 2$. We see that, as expected from the behavior depicted in Fig. 4, for $\tilde{\zeta} / \lambda < 1$, the distribution function $f(\psi, t)$ will become increasingly peaked at $\beta < 90^\circ$. For $\tilde{\zeta} / \lambda > 1$, however, $f(\psi, t)$ evolves into a double-peaked function, with one of the peaks located around β_+ and the other close to 180° .

Obviously, to determine the true distribution $f(\psi, t)$ for an ensemble of planetary systems, one must further “average” over the distribution of $(\lambda, \tilde{\zeta})$ for different systems. These parameters are largely unconstrained. Nevertheless,

we can reasonably expect to see a significant number of systems concentrating at small ψ (all cases with $\tilde{\zeta} / \lambda < 1$), and the rest distributed between all possible values of β_+ (which is less than 90°), or close to $\psi = 180^\circ$.

6 DISCUSSION

We have shown in this paper that the angle between the spin axis of a magnetic protostar and the axis of its disc may have a wide range of values: some systems are expected to be aligned, but some are expected to be misaligned. As a result, we would expect the spin-orbit inclination angle in exoplanetary systems to have a broad distribution, with some systems aligned, while others highly misaligned, even without any additional/subsequent physical processes that may affect this angle.

While the results of this paper are compatible with the possibility that planet-planet scatterings or Kozai interactions play a role in determining the orbital characteristics of some close-in planets, they nevertheless weaken the challenges posed against the disc-migration scenario for the origin of most hot Jupiters. Most likely, both few-body interactions and disc migration are needed to explain the observed period distribution of exoplanetary systems.

Currently, there is no measurement of the spin-disc misalignment angle in any accreting T Tauri star systems, although in principle this angle may be constrained from spectropolarimetry observations (e.g., Hussain et al. 2009; Donati et al. 2010) and detailed modeling of the variabilities of T Tauri stars. Alternatively, spin-disc alignment may be tested by measuring the $v \sin i_*$ and the rotation period of the star, and comparing the resulting stellar inclination i_* with the disc inclination i_{disc} , which may be constrained from the jet direction (for T Tauri discs) or the sky-projected shape of debris discs⁷. On the theoretical side, the spin-disc misalignment angle is determined by the uncertain values of two dimensionless parameters, λ and $\tilde{\zeta}$ (see Section 4) and their possible dependence on various unknown quantities (such as the mass accretion rate), as well as on the initial condition (see Section 5) and the age of the disc-accretion phase. However, these two parameters may potentially be calibrated from observations of a large sample of T Tauri stars. With these input parameters, we can then compare theoretical predictions (which include not only the process studied in this paper but also few-body interactions that may change the spin-orbit angles) with the observed distribution of misalignment angles between planets’ orbits and the spins of their mature host stars (Triaud et al. 2010).

A more direct observational test is to measure the spin-orbit angle for multiple planets systems. Few-body interactions would produce different angles for different plan-

⁷ Recently, Watson et al. (2010) carried out such an analysis for several debris disc systems and found no significant difference between $\sin i_*$ and $\sin i_{\text{disc}}$. Note that $i_* = i_{\text{disc}}$ does not necessarily imply alignment between the spin axis and the disc axis. Also, systematic uncertainties in estimating i_{disc} need to be taken into account. For example, for HD 22049 (one of the best cases studied by Watson et al), the disc inclination is consistent with face-on ($i_{\text{disc}} \lesssim 25^\circ$; K. Stapelfeldt 2010, private communication; see Backman et al. 2009).

ets in the same system. In contrast, the magnetosphere – disc interaction studied in this paper would lead to the re-orientation of the stellar spin while preserving the orbital plane of the planetary systems. Up to now, there is no known multiple-planet systems with measured stellar spin and planet orbital angular momentum vector. In the context of the solar system, the orbits of most planets, including those of Jupiter and Saturn, are confined within $\sim 2^\circ$ from the ecliptic. Although the Sun’s spin vector is misaligned by 7° with the vector normal to the ecliptic plane of the solar system, this modest difference may or may not provide adequate support for the magnetosphere – disc interaction scenario.

According to the scattering/Kozai scenario, planets venture into the proximity of their host stars with a diverse degree of spin-orbit misalignment. Yet, the misaligned systems tend to have parent stars with mass greater than $1.2M_\odot$ (Schlaufman 2010; Winn et al. 2010). Based on this scenario, Winn et al. (2010) suggested that spin-orbit misalignment for planets around solar type stars has been damped out by tidal dissipation in the star, whereas such dissipation may be less efficient for more-massive stars (with $M > 1.2M_\odot$) because of their shallow or non-existent outer convection zones (e.g., Barker & Ogilvie 2009). Nevertheless, the tidal dissipation time scale is a rapidly increasing function of planets’ orbital semi-major axis. Therefore, according to the tidal interaction hypothesis, the spin-orbit misalignment may nonetheless be preserved for planets around solar type stars with periods longer than a few days.

In the scenario that the spin-orbit misalignment is induced by the magnetosphere – disc interaction, tidal damping of the misalignment angle can still operate more effectively around solar type stars than more massive stars. In addition, the magnitudes of λ and ζ and therefore the resultant value of β are functions of the stellar mass. In this case, the correlation between spin-orbit misalignment and the stellar mass would be independent of the planets’ orbital period (for periods longer than a few days). The confinement of multiple planets in a common orbital plane would also be preserved. These observational tests, though challenging, will eventually provide clues and constraints on the origin of hot Jupiters as well as that of the spin – orbit misalignment.

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